Handedness inside the proton

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Questions to be addressed:

Is there nonzero transversity of quarks inside *unpolarized* hadrons?
How would one be able to find this out?

The transverse polarization of a noncollinear quark inside an unpolarized hadron in principle can have a preferred direction

This preferred direction signals an intrinsic handedness
Why? For instance, in the infinite momentum frame:

$$S_T^q \sim P_{\mathsf{hadron}} \times p_{\mathsf{quark}}$$

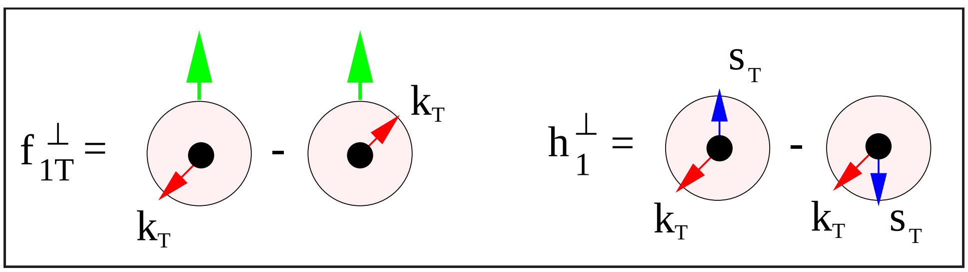
Obviously related to orbital angular momentum, but how exactly is still an open question

T-odd distribution functions

Such handedness appears to violate time reversal invariance
It is described by a T-odd distribution function, which was thought to be absent if the incoming hadron is treated as a plane-wave state

Recent work by Brodsky, Hwang, Schmidt, PLB 530 (2002) 99; Collins, PLB 536 (2002) 43; Ji, Yuan, hep-ph/0206057; Belitsky, Ji, Yuan, hep-ph/0208038 shows otherwise

Two leading twist (unsuppressed) T-odd distribution functions with transverse momentum dependence are possible



$f_{1T}^{\perp} \leftrightarrow$ Sivers effect (Sivers, PRD 41 (1990) 83; 43 (1991) 261)

$h_1^{\perp}$ signals an intrinsic handedness

$$h_1^{\perp} \neq 0 \leftrightarrow \text{Prob}\,[q(\boldsymbol{k}_T, \boldsymbol{s}_T)\,\text{in}\,P] \neq \text{Prob}\,[q(\boldsymbol{k}_T, -\boldsymbol{s}_T)\,\text{in}\,P]$$

Its phenomenology was presented in D.B. & Mulders, PRD 57 (1998) 5780 and D.B., PRD 60 (1999) 014012 & NPB (PS) 79 (1999) 638

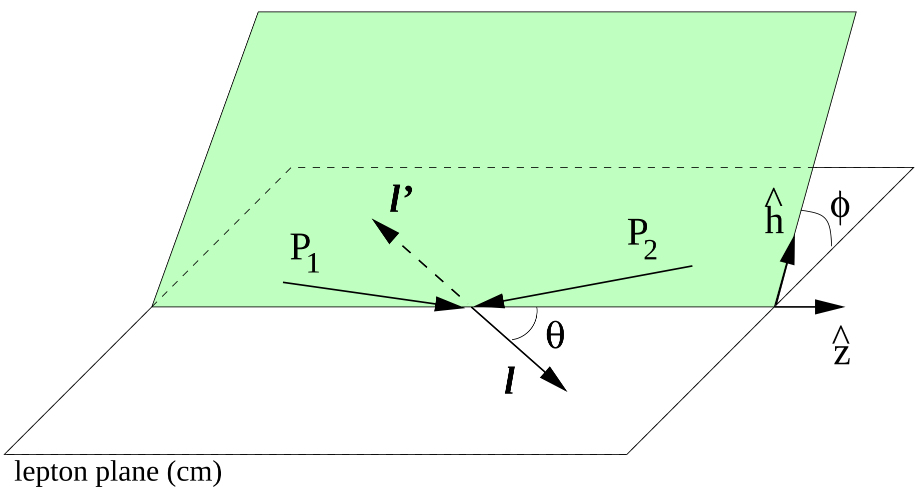
The unpolarized Drell-Yan process

There exists data compatible with nonzero $h_1^\perp$

Data from: NA10 Collab. ('86/'88); E615 Collab. at Fermilab ('89)
$\pi^- N \to \mu^+ \mu^- X$, with $N = D, W$ and π-beams of 140-286 GeV

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin^2\theta \, \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi\right)$$

Perturbative QCD prediction (NLO): $\lambda \approx 1, \quad \mu \approx 0, \quad \nu \approx 0$



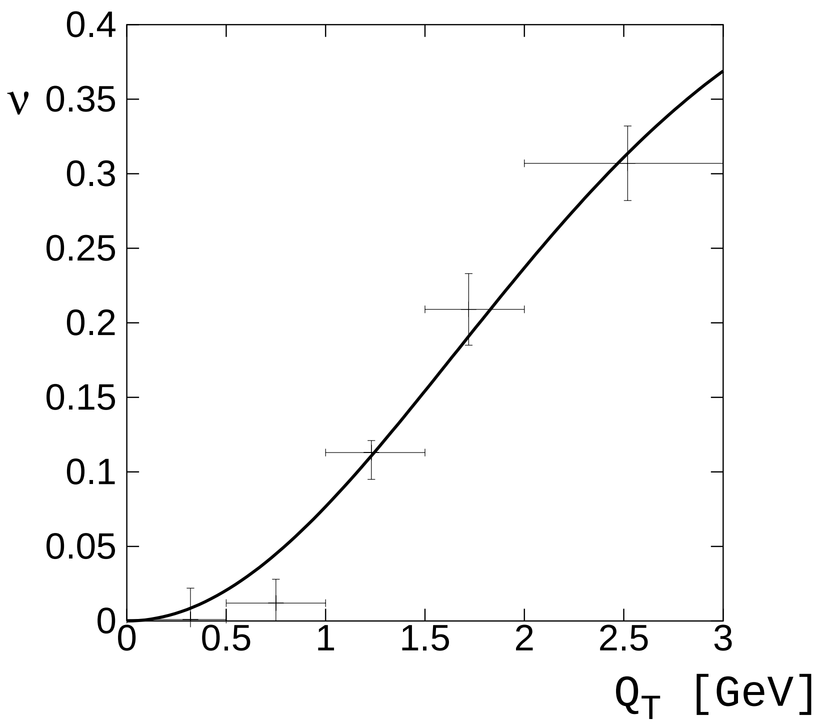
Data: large ν!

The unpolarized Drell-Yan process

The function $h_1^\perp$ can provide an explanation for this large $\cos 2\phi$

Brandenburg, Nachtmann & Mirkes (ZPC 60 (1993) 697): large ν arises from a factorization breaking correlation between π and N

Observation: $\nu \propto h_1^\perp(\pi)\, h_1^\perp(N)$ [D.B., PRD 60 (1999) 014012]
Use the data to fit the function $h_1^\perp$



No factorization breaking and offers a natural explanation for $\mu \approx 0$

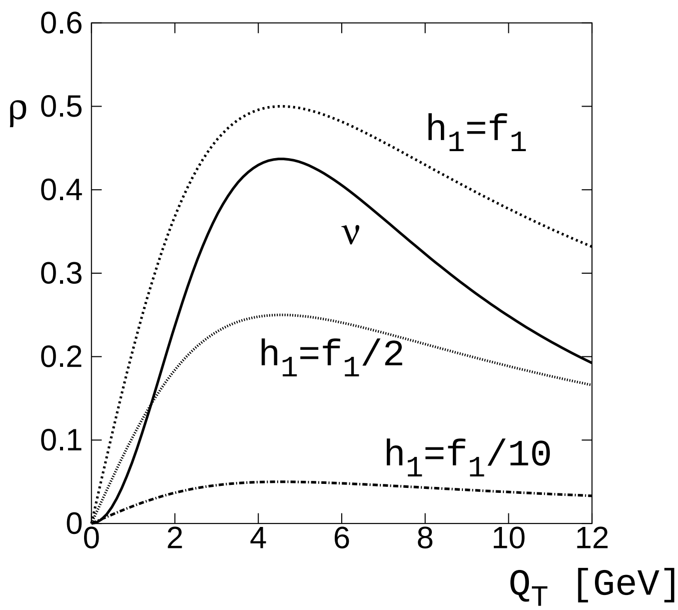
The polarized Drell-Yan process

In the case of one polarized hadron (choosing $\mu = 0$ and $\lambda = 1$):

$$\frac{d\sigma}{d\Omega\, d\phi_S} \propto 1+\cos^2\theta+\sin^2\theta \left[\frac{\nu}{2}\, \cos 2\phi - \rho\, |\boldsymbol{S}_{1T}|\, \sin(\phi+\phi_S)\right]+\ldots$$

Relation for the case of one flavor: $$\rho = \frac{1}{2}\sqrt{\frac{\nu}{\nu_{\text{max}}}}\,\frac{h_1}{f_1}$$

Yields as crude predictions



Different angular dependence compared to the Sivers asymmetry

$$(1+\cos^2\theta)\, |\boldsymbol{S}_T|\, \sin(\phi-\phi_S)\; f_{1T}^{\perp} f_1$$

Further remarks

Possible future DY data

RHIC: $\langle \cos 2\phi \rangle$ in unpolarized $p\,p \to \mu^+\mu^- X$ and the single spin asymmetry $\langle \sin(\phi + \phi_S) \rangle$, which is proportional to $h_1\, h_1^\perp$

Fermilab: $\langle \cos 2\phi \rangle$ in $p\,\bar{p} \to \mu^+\mu^- X$ probably yields larger results

Semi-inclusive DIS

The $\langle \cos 2\phi \rangle$ in SIDIS seems to be smaller than the $\langle \cos 2\phi \rangle$ in DY, but also smaller than the $\langle \cos \phi \rangle$ indicating that hard gluon radiation could be the explanation in SIDIS

In the present picture the $\langle \cos 2\phi \rangle$ in SIDIS would be $\propto h_1^\perp H_1^\perp$, hence this could be a sign that the magnitude of $H_1^\perp$ is smaller than that of $h_1^\perp$

Testable by comparing to $\langle \cos 2\phi \rangle$ in e^+e^- annihilation (BELLE, BABAR)

Another test would be to look at $\langle \cos 2\phi \rangle$ for a jet instead of a hadron, $e\,p \to e'\,\text{jet}\,X$; $h_1^\perp$ should then not contribute

SSA in hadron-hadron collisions

Single spin asymmetries in $p + p^{\uparrow} \to \pi + X$

These can arise from leading twist T-odd functions with transverse momentum dependence in three different ways:

- Distribution functions: $f_{1T}^{\perp}(x_1, \boldsymbol{p}_T) \otimes f_1(x_2) \otimes D_1(z)$
  $h_1^{\perp}(x_1, \boldsymbol{p}_T) \otimes h_1(x_2) \otimes D_1(z)$
- Fragmentation functions: $h_1(x_1) \otimes f_1(x_2) \otimes H_1^{\perp}(z, \boldsymbol{k}_T)$

Options 1 & 3 investigated by Anselmino, Boglione & Murgia (PLB 362 (95) 164 & PRD 60 (99) 054027)

The Collins effect, $H_1^{\perp}(z, \boldsymbol{k}_T)$, is expected to be present in quark fragmentation, but its magnitude is in principle unrelated to $h_1^{\perp}(x_1, \boldsymbol{p}_T)$

Options 1 & 2 also occur in $p + p^{\uparrow} \to$ jet $+ X$

Polarized Λ production in SIDIS

Polarized Λ production in semi-inclusive DIS

The intrinsic handedness can also lead to the following asymmetries:

- $\sin(\phi^e_\Lambda + \phi^e_{S^\Lambda_T})$ asymmetry in $e\,p \to e'\Lambda^\uparrow X$
- $\sin(2\phi^e_\Lambda)$ asymmetry in $e\,p \to e'\vec{\Lambda}X$

These distinct angular dependences should be absent for charged current exchange processes, like $\nu\,p \to e\Lambda^\uparrow X$ or $\nu\,p \to e\vec{\Lambda}X$
D.B., Jakob & Mulders, NPB 564 (2000) 471

Distinguishable from other mechanisms via y or ϕ^e dependence
E.g. the polarizing fragmentation functions in SIDIS
Anselmino, D.B., D'Alesio & Murgia, PRD 65 (2002) 114014

Moreover, it should vanish after integration over Q_T, leaving only a $\sin(\phi^e_{S^\Lambda_T})$ asymmetry (twist-3)

Conclusions

Leading twist T-odd distribution functions with transverse momentum dependence can offer viable explanations of certain azimuthal asymmetries

The intrinsic handedness function $h_1^\perp$ can explain:

- the $\cos 2\phi$ asymmetry in unpolarized Drell-Yan
- single spin asymmetries in $p + p^\uparrow \to \pi + X$

Furthermore, it can generate

- $\sin(\phi + \phi_S)$ in $p\,p^\uparrow \to \mu^+\mu^- X$
- $\cos 2\phi$ in $e\,p \to e'\,\pi\,X$, but not $e\,p \to e'$ jet X
- $\sin(\phi_\Lambda^e + \phi_{S_T^\Lambda}^e)$ in $e\,p \to e'\Lambda^\uparrow X$ (NC, but not CC)
- $\sin(2\phi_\Lambda^e)$ in $e\,p \to e'\vec{\Lambda} X$ (NC, but not CC)

There are several ways of differentiating between mechanisms

Testable (in principle) using a host of existing (Fermilab, BELLE, ...) and future data (RHIC, COMPASS, HERMES, ...)